Plasma Ignition in a 30mm Cannon

Richard A. Beyer and Andrew L. Brant

U.S Army Research Laboratory, Aberdeen Proving Ground, Maryland

Abstract — Plasma ignition of conventional propelling charges has been studied in a 30 mm cannon using plasma generated in a capillary external to the charge. It is shown that the interaction distance for strong response from a propellant is limited even for this caliber that may have implications for pressure wave formation during ignition. The use of confinement of a portion of the charge for enhanced ignition is shown to result in the most prompt ignition. However with JA2 propellant direct action of the plasma on the charge produces good results. The effect of plasma pulse length is explored; observations that enhanced radiation from high peak power increases propellant response to plasma are discussed. A limited comparison of the response of JA2 and M30 propellants has been made.

I. Introduction

The application of electrically generated plasma ignition for medium and large caliber cannons has been explored by several research groups. The promise of prompt ignition of charges, ignition of insensitive propellants, and possible compensation for propellant burning rate variation with temperature have been both touted and sometimes demonstrated. While plasma ignition is attractive, the size of the power supplies and pulse forming network components have excluded this technology from consideration for use in near-generation large caliber weapons systems. The primary goal of the present study is to apply the knowledge base of plasma-propellant interactions developed in our laboratory and to attempt to demonstrate a more efficient use of the stored electrical energy by maximizing that interaction. The approach is to vary both physical and electrical design parameters. Although not presently complete, we describe here the beginning of a series of medium-caliber cannon firings from which design parameters may be extracted for larger calibers.

In our previous studies [1] of plasma-propellant interactions, it was demonstrated that the primary characteristic which distinguishes these plasmas from conventional ignition is the interaction of the plasma visible and infrared light to generate enhanced surface area in translucent propellants (e.g. M9 and JA2, especially graphite-free JA2). While traditional propellant ignition wisdom dictates that overdriving the process with a short pulse can be inefficient, since the chemistry of heat release isn't fast enough, a

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Plasma Ignition in a 30mm Cannon**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Research Laboratory,Aberdeen Proving Ground,MD,21005**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS
resented at the 13th International Symposium on Electromagnetic Launch Technology (EML), Held May 22 - 25, 2006 in Potsdam, Brandenburg, Germany Copyright 2006 IEEE. Published in the Proceedings, http://emlsymposium.org/archive.html#

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

short plasma pulse with higher peak power (for the same energy content) generates much more light and greatly enhanced surface area generation. This possible trade off between short-pulse plasma effects and longer-pulse chemical interaction effects is also explored.

II. EXPERIMENTAL

The electrical energy for the discharge was provided by a conventional pulse-forming network (PFN) power supply consisting of 600 μF of capacitance, 15 mH inductance, and an electronic switch. Fully charged to 3 kV the stored energy was somewhat less than 3 kJ. Pulse length ("short pulse") was about 300 μs. For a limited number of "long-pulse" shots, an additional 40 mH of inductance was added to increase the pulse length to about 900 μs. Energy in the plasma discharge was typically 2.1 to 2.3 kJ for the work described here. The plasma for these experiments was generated by a discharge in a 3.17-mm (0.125-inch) i.d. polyethylene capillary approximately 35 mm long.

The primary propellant used here for enhanced plasma-propellant interaction is JA2 sheet processed without the usual 0.05 percent graphite, referred to as graphite-free JA2 or GF-JA2. JA2 is a modified double-base propellant consisting of nitrocellulose with nitroglycerin and diethylene glycol nitrate (DEGDN) plasticizers. Average sheet thickness is 2.54 mm. The mass of GF-JA2 in the igniter tube varied from 1.6 to 1.9 g which contains about 8.1 to 9.6 kJ of chemical energy.

The propellant used in the gun charges were standard JA2 and M30. M30 is a triple base propellant in which the major constituents are nitrocellulose, nitroglycerin and nitroguanidine. The M30 grains had seven 0.3-mm diameter perforations with inner web of 0.25 mm, outer web of 0.42 mm, and length of 4.7 mm. The JA2 grains had a single perforation of 0.41 mm diameter, web of 0.87 mm and length of 4.8 mm.

The conventional ignition system used consisted of an M52A3B1 electric primer and solid strands of benite (black powder embedded in strands of nitrocellulose) 13.3 cm long with a total weight of 1.5 g with calculated chemical energy of about 3.7 kJ.

III. OBSERVATIONS AND ANALYSIS

SMALL-SCALE

In making the transition from fundamental studies of plasma-propellant interactions to the design of a practical gun igniter, one important element was to determine the level of interaction of the plasma with either the propellant bed or material in a special igniter tube. Both the use of minimal plasma energy and yet a fairly uniform ignition of the propellant bed are desirable. That is, localized, robust base ignition is not desirable since it would not be effective in a larger caliber cannon. A simple fixture was used to explore the distance over which plasma on this scale would affect graphite-free JA2, which is our most-studied material.

The fixture contained a capillary discharge that produced a plasma that was directed through the cathode and an orifice of variable length and diameter into an open-ended chamber of square cross section (6.35 mm by 6.35 mm by 100 mm). Two opposite walls of the chamber were made from 2.54-mm thick propellant sheets that extended the length of the flow channel. They were backed by acrylic sheet to hold them in place. The other walls were aluminum.

The observations are difficult to quantify, but two trends are suggested. The flow channel between the capillary and the propellant should be as short and as large in diameter as reasonable to maximize interaction. It also appears that the channel should be reasonable smooth; an attempt with the nozzle removed and 3/8-24 threads exposed to the flow resulted in reduced interaction from the largest diameter channel. Future efforts to scale up to large caliber guns should include modeling to explore the formation of shock waves and their effect on plasma penetration.

A photograph of the propellant sample from the test with the longest interaction region, from a 16-mm long nozzle with 5.6-mm orifice, is shown in Fig 1. As can be seen there, the interaction is strong and penetrates the sample, but extends less than 6 cm or about one-third the length of our gun chamber. Based on this series of observations it was decided to mount the capillary as close as possible to the propellant bed with only the 3-mm thick cathode between the discharge and ignition tube (bayonet). Possible changes in shock formation with longer pulses and lower velocities were not explored.

A second fixture was constructed to explore the pressure-time behavior of the propellant in a vented igniter tube. A schematic diagram of this apparatus is shown in Fig. 2. It was configured to mimic a bayonet igniter tube that might be used with the 30-mm cannon. The propellant is a 6-mm wide, 101-mm long strip cut from 2.54-mm thick sheet propellant (either GF-JA2 or standard JA2). The primary diagnostic was pressure as measured at the end of the tube, as shown. The 32 vent holes (1.59 mm diameter) were chosen as a balance between the conflicting needs for confinement of the propellant to enhance rapid combustion but also for sufficient venting to prevent over-pressurization and ultimately to provide ignition of the main charge.

Tests were done with both standard and graphite free JA2 in the igniter tube. The results of typical traces are shown in Fig. 3. The first feature to note is the amount of "prompt" pressure generated during the discharge from the direct interaction of the plasma with the propellant. It has a relatively weak dependence on the energy (power) of the discharge; the amount generated with GF-JA2 is greater than with the standard JA2, but only perhaps twenty five percent more. The second feature is the pressure generated from the combustion of the bulk of the propellant. With the transparent propellant the pressure rise is more prompt, especially with the lower energies (except at 1.0 kJ). Because of the promptness and magnitude of the pressure response it was concluded that this configuration at energies above 1.5 kJ should make an effective igniter.

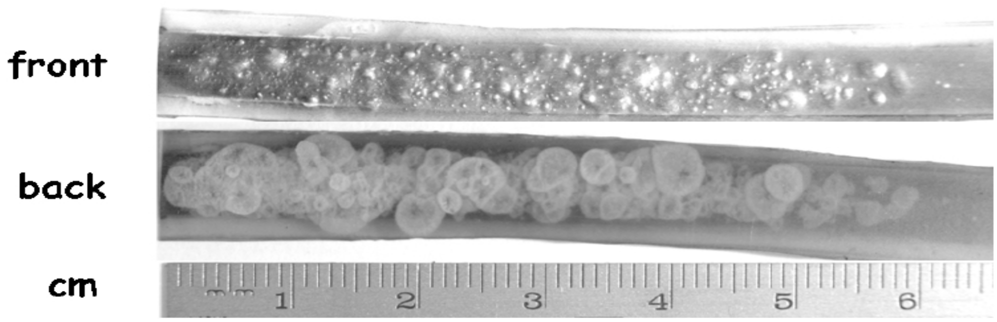

Fig. 1. Photographs of GF-JA2 propellant following plasma channel experiment.

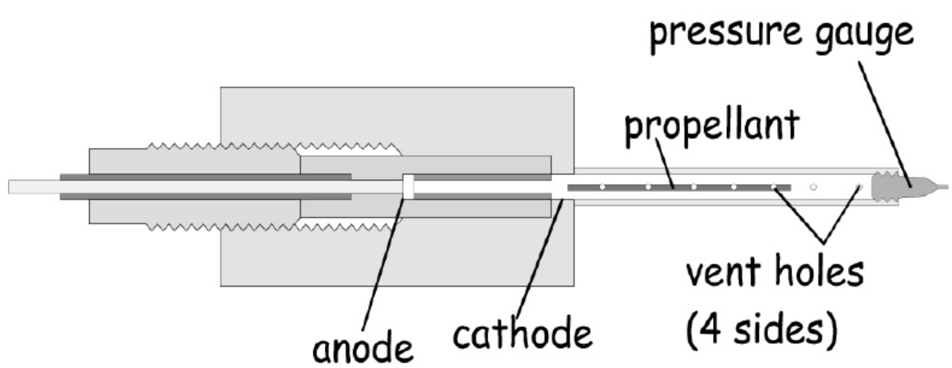

Fig. 2. Schematic of igniter fixture used to characterize plasma ignition of JA2 strip.

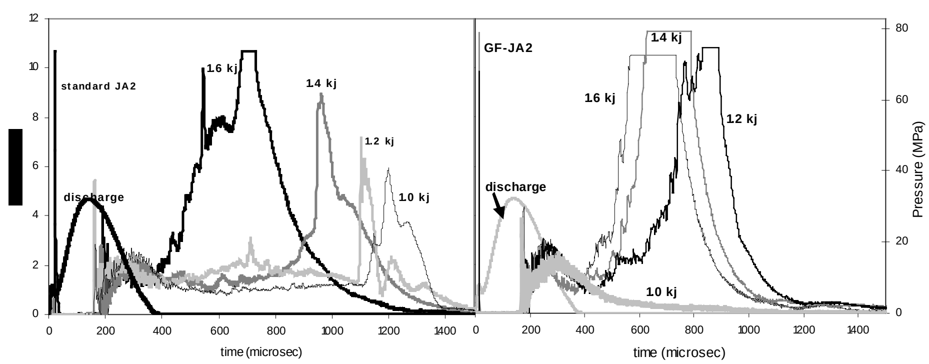

Fig. 3. Pressure measured inside the igniter tube of Fig. 2.

30-MM CANNON FIRINGS

The 30-mm experimental gun fixture used here consists of a simple screw breech chamber with a 38 mm inside diameter threaded to a 2.5 m long gun tube on a Frankford gun mount. The chamber to barrel seal system consists of an o-ring, nested inside a steel wedge ring. The gun and breech have been described in detail previously [2]. For the work presented here, pressures were measured at two positions in the chamber, labeled as P1 (breech) and P2 (barrel).

Three ignition configurations were used for most of the shots. All had a similar geometry and dimensions. They were (1) a baseline electric primer with benite in the tube, (2) plasma injected into an empty tube and interacting directly with the propellant bed, and (3) plasma injected into the tube with a strip of JA2 (standard or graphite-free) in the tube. Two shots were done with the empty bayonet replaced with a 6-mm diameter plastic straw that was firmly mounted into the stub case. One of these was an empty straw into the propellant bed. The second straw shot had a 101-mm long "box" of GF-JA2 affixed to it. All plasma shots were attempted with the same stored energy and discharge energy near 2.2 kJ. A summary of the pressure-time records is shown in Fig. 5 with identifications in the Table. These records as plotted are the averages of the two pressure gauges in the chamber. Peak pressure values are not important and could be affected by variables such as heat transfer to gauges; they have no significance. Of note in Fig. 5 is that the promptness of response was increased by a strong interaction of propellant with the plasma (GF-JA2 being more responsive than standard JA2) and also was increased by the confinement of the portion of the propellant in the igniter tube. The attempt to increase the plasma-propellant interaction with a "box" of GF-JA2 around the straw (shot E) was probably hindered by the forces involved which may have moved the propellant before a strong plasma response was present. The comparisons of short and long pulse are consistent with the earlier hypothesis that higher peak power (and corresponding higher light emission) provides a strong propellant response. However these limited gun-firing data do not demonstrate this convincingly.

The case for these tests is a stub case with 3.17 mm (0.125") thick polycarbonate walls. This yields an initial chamber volume of 135 cc. The projectile used in these tests is a mild steel slug with a thread-on polypropylene obturator. Projectile mass was near 550 grams. Shot-start was very low for this system as configured for these shots, approximately 1100 psi. A schematic of the cartridge is shown in Fig. 4.

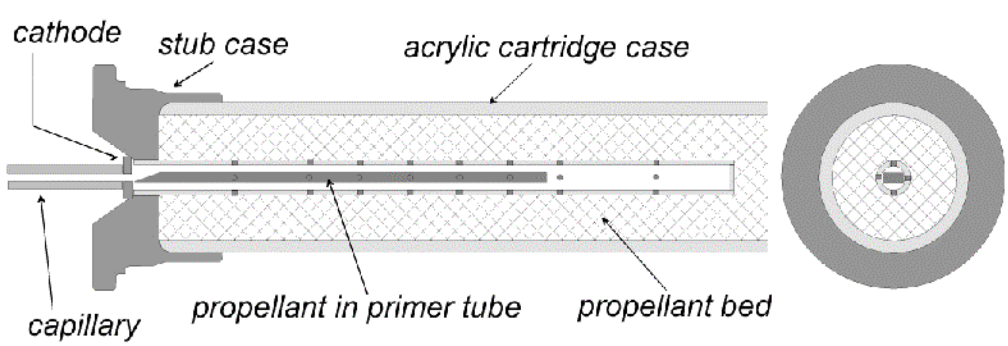

Fig. 4. Schematic of 30-mm stub-case cartridge with plasma injection.

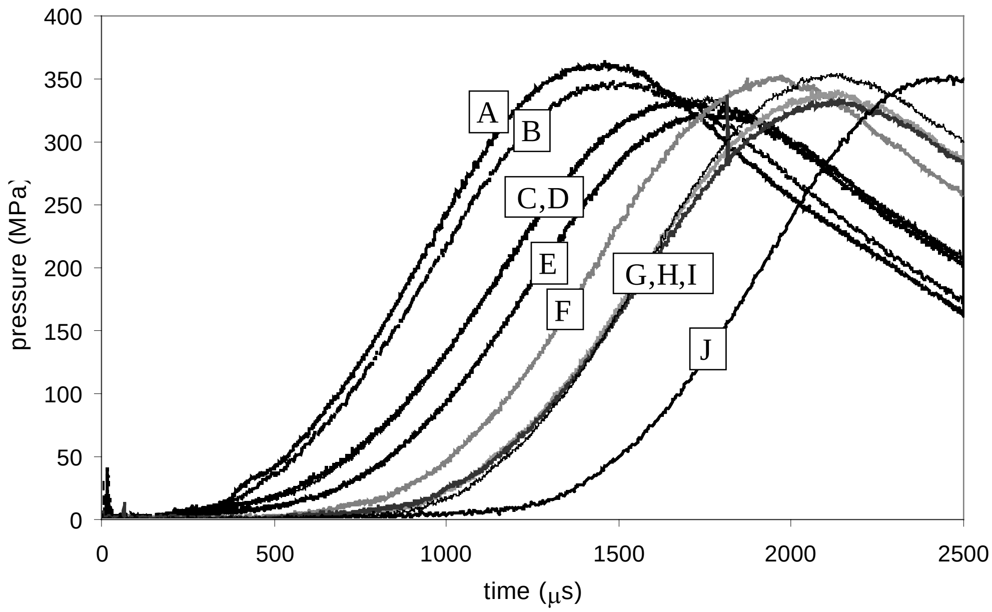

Fig. 5. Pressure-time records for 30-mm cannon with JA2 propellant for various ignition schemes.

TABLE: Key to pressure traces in Figs. 5, 6, and 7.

Ignition Configuration	Pulse	Full Trace Fig. 5	Early Time Trace
GF-JA2 in bayonet	Short	A	Fig. 6, trace #1
Standard JA2 in bayonet	Short	B	Fig. 6, trace #2
Empty bayonet	Short	C	Fig. 6, trace #3
Soda straw in center of charge	Short	D	Fig. 6, trace #4
GF-JA2 "box" w/straw	Short	E	
GF-JA2 in worn bayonet	Long	F	Fig. 7, trace #3
GF-JA2 in new bayonet	Long	G	Fig. 7, trace #4
Empty bayonet	Long	H	Fig. 7, trace #1
Empty bayonet	Long	I	Fig. 7, trace #2
Electric primer & Benite in bayonet	-	J	

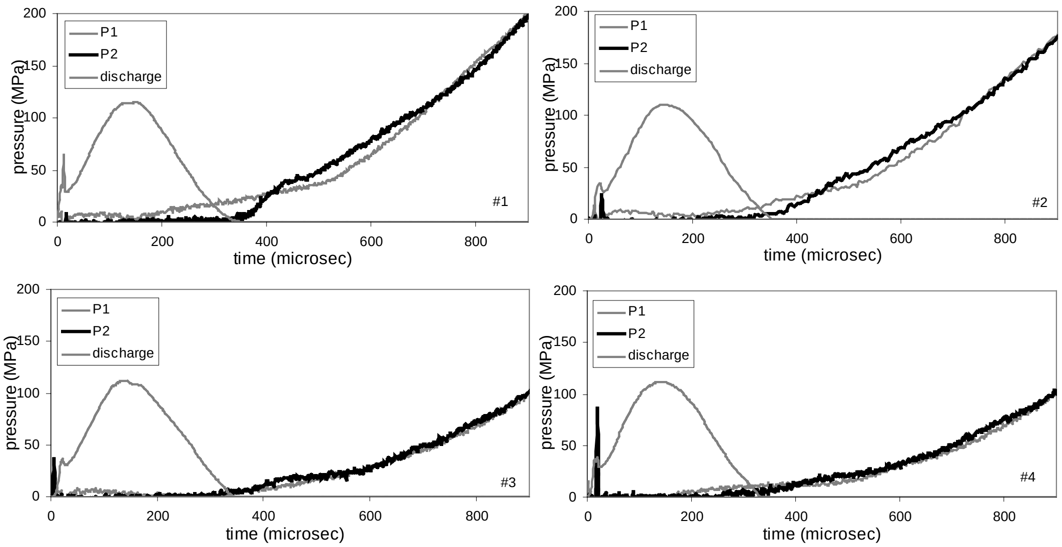

Fig. 6. Early pressure behavior with short-pulse plasma

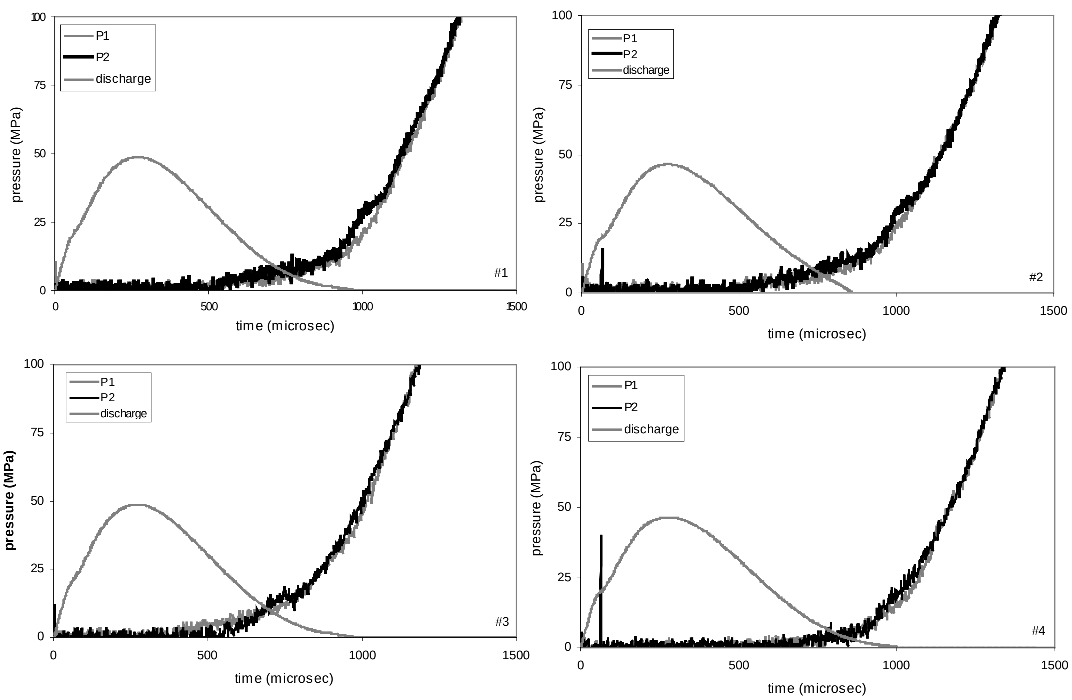

Fig. 7. Early pressure behavior with long-pulse plasma.

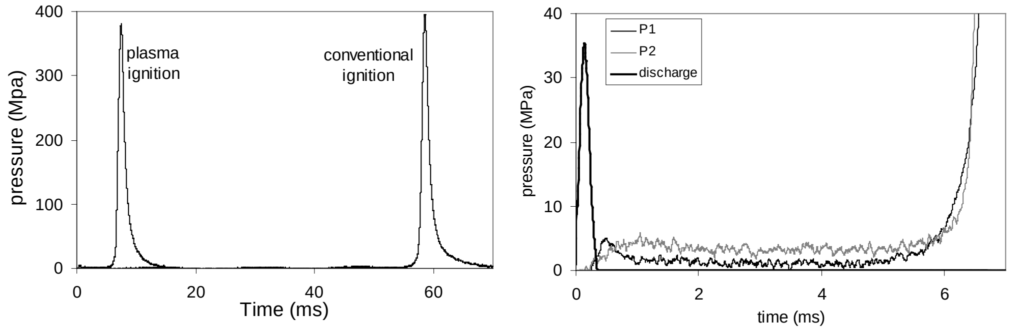

Fig. 8 Pressure records with M30 propellant showing plasma and conventional ignition (left) and the early pressure behavior with plasma ignition (right).

The position of the capillary and anode relative to the cartridge is shown in Fig. 4. This assembly was designed with the discharge close to the gun cartridge in order to maximize the plasma-propellant interaction. These components, the electrical insulators and wires were fitted inside a modified igniter assembly and screw breech of the previous tests [2]. The bayonet igniter tube was 9.5 mm (3/8 in.) o.d., 6.3 mm (0.25 in.) i.d., and 152 mm (6 in.) long. It had 32 vent holes approximately as shown that were initially 1.59 mm (1/16 in.) in diameter.

The plasma eroded the vent holes in the bayonet ignition tube during the course of these observations more than was realized during the tests. As might be expected, orifices closest to the cathode had the greatest enlargement. Although it was judged at the time to be a secondary effect, in a single direct comparison (F and G in Fig. 5) the larger vent holes appeared to improve ignition of the long pulse plasma with GF-JA2 in the ignition tube. Yet shots labeled C and D comparing an empty bayonet with the thin plastic straw indicate that for direct plasma interaction with the propellant bed the tube serves only to provide a flow path through the propellant bed. The possibility was considered that shock heating of the plasma exiting the vent holes would generate high temperatures locally. This was based on our earlier observations [5] of extreme temperatures in plasma shock structures. This effect does not appear to be present with the bayonet.

Details of the initial pressurization of selected experiments are shown in Figs. 6 and 7. Note that scales of these two figures are different. Notable in the short-pulse observations (Fig. 6) is the small but significant pressure rise during the plasma pulse. This pressure rise is sufficient to accelerate the heat release and continued reaction of the propellant bed so that the charge transitions promptly to full ignition. There are some small pressure waves as seen in Fig. 6 which are gone by 1 ms. In contrast the pressurization of the long pulse data shown in Fig. 7 is smoother with less early pressure boost from the plasma and smaller waves that are gone at about the same time as with the short pulse ignition.

For comparison with a second propellant, M30 charges were ignited under conditions similar to that of the JA2. The plasma ignition used 1.7 g of GF-JA2 in the bayonet igniter tube and 2.2 kJ of electrical energy with a short pulse. As can be seen in Fig. 8 (left) the plasma-ignited round had action time of about one-tenth of the conventionally ignited round. The early pressure behavior on the magnified scale (Fig. 8, right) shows the significant pressure boost from the plasma that would be expected to produce the decreased ignition time, as observed. Direct plasma ignition of the M30 charge was attempted at least twice using an empty bayonet igniter tube and similar plasma energy as with other tests in this series without successful ignition. The recovered grains did show evidence of partial burning and perf enlargement on a very limited scale as evidence that the plasma did couple effectively into the bed. However in contrast to the JA2 charge, the level of pressurization observed following the plasma interaction, about 0.8 MPa for 5 ms, was not sufficient to bootstrap the M30 charge. For comparison between M30 and JA2 charge ignition, the left part of Fig. 8 is comparable to traces A and J in Fig. 5.

IV. DISCUSSION

As stated at the outset, the goal of this study is to determine the controlling parameters of plasma ignition and eventually to develop "design rules" for efficient plasma ignition of gun charges. In our previous analysis [3] of the cause of observed plasma-ignition benefits, the key was argued to be a rapid early pressurization of the charge. The present observations further support that hypothesis. In demonstrations of high-energy plasma (Electro-Thermo Chemical) igniters the rapid pressurization can take place throughout the charge simply by a combination of overwhelming the charge with an abundance of hot, highly mobile plasma. The tolerance of stick charges to uneven pressurization has probably been a key factor in the success of this approach.

If we are to achieve a measure of success with significantly lower electrical energy in the igniter, it would appear that a strong localized coupling between the plasma and a limited but distributed portion of the charge is required. This end might be achieved either with mechanical structures such as our bayonet igniter tube, which could be made of combustible material, or by a discharge located inside the propellant bed, but which interacts with a limited and well-defined portion of the charge. This conclusion is due in part to the continuing evidence that (a) the strongest interaction for generating controlled increases in propellant surface area is due to the visible and infrared radiation from the discharge and (b) the distance that a plasma can penetrate a charge while maintaining the properties essential for this interaction are limited, especially if decreased electrical input is desired.

Thus we conclude that more electrically efficient plasma ignition will require a fundamental change in the design of the charge and plasma ignition system to satisfy space and charge weight limitations. It is clearly physically possible to meet the efficiency goals but further research and a bit of clever design work remains to be done.

V. SUMMARY

We have shown here that moderate amounts of plasma energy can be used in conjunction with a relatively insensitive gun propellant to provide prompt and repeatable ignition. It is observed that although one of the features of plasma is its low molecular weight and high penetration of a charge the strongest plasma-propellant interaction is radiative. It appears that the plasma is interacting strongly with the charge (or igniter tube material) over only a limited distance. Under some conditions the localized effects of plasma in a bayonet primer may promote the formation of pressure waves in a granular propellant bed. While this effect may be mitigated by a design with sealed vent holes to allow pressure equalization in the bayonet, care must be taken to minimize pressure waves while maintaining prompt ignition and minimizing the plasma energy required.

The results with ignition of M30, in particular the prompt response observed, has encouraged the exploration of obtaining candidate next-generation insensitive propellants in suitable configuration for testing in this same fixture.

REFERENCES

[1] R. A. Beyer and R. A. Pesce-Rodriguez., "The Response of Propellants to Plasma Radiation," *IEEE Trans. Mag*. Vol. 41, No. 1, pp 344-349, Jan. 2005.

[2] J. W. Colburn, A. W. Johnson, M. B. Ridgley, D. E. Kooker, T. C. Minor, "The Effects of Base Ignition on Slab Propellant in a 30-mm Short Gun," *Proceedings of the 35th JANNAF Combustion Subcommittee Meeting*, CPIA Publication 680, Volume I, pp. 79-89, December 1998.

[3] R. A. Pesce-Rodriguez, and R. A. Beyer, "A Theory of Plasma-Propellant Interactions," *Army Research Lab. Tech. Rep.t ARL-TR-3286*, 2004.

[4] L.-M. Chang, and S. L. Howard, "Electro-Thermal Chemical (ETC) Plasma Ignition of Gun Propelling Charges: The Role of Pulse Length," *39th JANNAF Combustion Subcommittee Meeting*, Colorado Springs, 2004.

[5] Beyer, R. A., and Bunte, S. W. "Spatial and Temporal Temperature Studies of Electrothermal Chemical (ETC) Plasmas," *Ballistic Res. Lab. Tech. Rept. BRL-TR-3324*, 1992.